Forest Fertilization and Water Quality in the United States

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When proper best management practices (BMPs) are employed for forest fertilization, changes in streamwater chemistry are very slight and there have been no detectable effects on the composition or productivity of stream aquatic communities. Short-term increases in peak concentrations of NO_3^-, NH_4^+, and P_2O_5 in streamwater can occur after forest fertilization. Increases in average concentrations are much lower than the peak values. High concentrations of nutrients in streamwater tend to occur when fertilizers are directly applied to streams, with repeated fertilization, with use of NH_4-NO_3 rather than urea as the N source, or with fertilization of "N-saturated" hardwood forests.

Forest fertilization is a widespread silvicultural practice in two regions of the U.S. In the southern states, over 1.2 million acres of pine plantations were fertilized with P or N+P in 2005 (see photo below). In the Pacific Northwest, operational fertilization is also a common treatment with about 100,000 acres of forest fertilized annually. The main tree species fertilized in the South are loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*). In the Pacific Northwest, the main species is Douglas fir (*Pseudotsuga menziesii*). In forestry, N is commonly applied as urea or DAP. Phosphorus is applied as either triple superphosphate or DAP. The cumulative growth response of loblolly pine plantations following mid-rotation fertilization with N+P is approximately 450 ft^3/A over 8 years. In Douglas fir stands, volume growth may increase 20 to 30% following N fertilization. Returns from forest fertilization can be financially attractive, sometimes in excess of 15%, depending on factors such as fertilizer cost and the value of the timber produced.

Approximately 80% of the freshwater resources in the U.S. originate from forested watersheds. The quality of water draining forests is typically higher than the quality of water draining areas under any other major land use (see photo above right). In the U.S., the concentrations of total N and P in water draining agricultural areas are about 9 times greater than concentrations found in forested streams. The concentration of NO_3-N may average about 0.23 mg N/L for very large forested watersheds in the U.S., compared with 3.2 mg N/L for streams in a number of large agricultural watersheds.

High quality water in a stream flowing from a forested watershed.

Forest fertilization of a slash pine stand in Florida with a forested buffer strip in the background.

Although the overall quality of water draining forest landscapes is very high, some forest practices, such as fertilization, may potentially alter water quality. Over the last 25 years, many studies, including several reviews, have been published. They generally concluded that forest fertilization poses little or no risk to water quality parameters when proper BMPs are implemented.

Streamwater Responses to Forest Fertilization

Fertilizer applications may alter streamwater chemistry across temporal and spatial scales. The transformation and subsequent movement of nutrients supplied in fertilizer determines the potential impact on water quality. Urea fertilization typically leads to immediate increases in urea-N concentrations in soils. Urea hydrolysis is relatively rapid in forest soils—as in agricultural soils—leading to rapid formation of NH_4^+. Ammonium oxidizes to form NO_3^- over periods of weeks to months following fertilization. Ammonium concen-

Abbreviations and notes for this article: NO_3^- = nitrate; NH_4^+ = ammonium; NH_4-NO_3 = ammonium nitrate; P_2O_5 = phosphate; P = phosphorus; N = nitrogen; DAP = diammonium phosphate; mg/L = milligrams per liter.

trations in soils tend to increase over a period of weeks or months, and NO_3^- concentrations may be increased for a period of a year or more following fertilization. Nitrate is much more mobile in soils and has a greater potential for transport to streams. The P concentration in soils following P fertilization is determined primarily by the rate of fertilizer applied and P adsorption capacity of soils. The P sorption capacity of most forest soils is high and there is generally little movement of P to streams over time from forest soils.

Without fertilization, the concentrations of NO_3-N observed in most forested streams are <1.0 mg/L. Most fertilization studies have shown peak concentrations of NO_3-N <2.0 mg/L following fertilization, but NO_3-N peaks from 10 to 30 mg/L can occur. Some of the highest values observed have been in several studies in the Fernow Experimental Forest in West Virginia. Forests at this site appear to be almost "N saturated", and fertilization led to high NO_3-N concentrations in streamwater, regardless of form of N applied (urea, NH_4-NO_3, or ammonium sulfate). However, hardwood forests in this region are almost never operationally fertilized with N.

Ammonium-N concentrations (maximum and annual averages) are usually very low in streams draining unfertilized forests. Fertilization typically has only marginal effects on NH_4^+ concentrations, except when N fertilizer is added as NH_4-NO_3. Streamwater standards for NH_4-N are rarely exceeded following fertilization.

Average concentrations of total P are also generally very low in streams draining unfertilized forests, but P fertilization can increase the average P concentration by several fold. Transient peaks in P concentrations are not uncommon following P fertilization. We expect that the transient timing of increases in P concentration, coupled with P removal and dilution downstream, probably result in little overall effect on aquatic ecosystems.

The fertilizer material used and the rate applied to the forest also have an impact on streamwater. Streamwater NO_3^- concentrations tend to be increased more by the application of NH_4-NO_3 than by urea. Since NH_4-NO_3 is seldom used in forestry, the impact of forest fertilization on stream NO_3^- is likely to be small, particularly when forested buffer strips are used. Nitrate concentrations in streams tend to increase with the number of times fertilizer is applied during a rotation. In a study with 23 fertilized stands, streams in unfertilized stands averaged about 0.3 mg NO_3-N/L, compared with 0.6 mg NO_3-N/L for areas fertilized once, and 1.0 mg/L for areas fertilized two or three times. Although higher rates of fertilizer may affect streamwater NO_3^- concentrations, even relatively high fertilization rates typically do not lead to NO_3^- levels that exceed water quality standards.

Elevated nutrient concentrations in streamwater following fertilization tend to become diluted relatively quickly downstream, as a result of nutrient uptake, transformation into gases, or dilution with additional water. Forest fertilization will typically not degrade water quality relative to drinking water uses, considering that even high peaks of NO_3^- concentration typically last a few days or weeks at most, and that dilution in downstream waters should reduce high NO_3^- concentrations by more than an order of magnitude within several miles of the fertilized site. It is also important to note that unlike with agricultural crops—where fertilizers may be applied several times each year—even in the most intensively managed forests, fertilizers are typically applied only 3 or 4 times during a 20 to 40-year rotation.

Forested buffer strips are established along intermittent streams in the Coastal Plain of the southern U.S. to protect water quality as a forestry BMP.

Role of Forested Buffer Strips in Maintaining Streamwater Quality

Because the major impacts on water quality occur when fertilizers are applied directly to streams, forestry BMPs recommend that forested buffer strips be established as streamside management zones (SMZs) to protect water quality when forests are fertilized (**see photo above**). The minimum width of the SMZ is generally 30 to 50 ft. In many states, wider SMZs may be required depending on the type and size of the stream, and the adjacent topography. In Virginia for example, the width of the SMZ ranges from 100 to 200 ft., depending on the slope of the adjacent land, around streams and lakes that serve as municipal water supplies.

A variety of studies have documented the efficacy of forested buffer strips in moderating flows of chemicals from agricultural lands into streams. For example, NO_3^- movement to streams can decrease by more than 80% in agricultural areas where streamside forest buffers are used. Phosphate is also effectively removed by forested buffers. Up to 99% of the P_2O_5 moving from agricultural fields can be removed in forested buffer strips. Much of the P_2O_5 that moves from agricultural fields is adsorbed to soil particles, and forested buffer strips are very effective at trapping sediment and associated P.

Buffer strips can also substantially reduce the urea-N and NH_4-N in streamwater. The effects on NO_3-N concentrations are likely to be smaller. A buffer strip approximately 15 ft. wide (50 m) can reduce concentra-

Precision application of fertilizer to selected forest stands in the southern U.S. uses satellite navigation.

tions of urea and NH_4^+ by about an order of magnitude (relative to the treatment without buffer strips), and reduce the concentration of NO_3 by about 60%. The reduction in urea and NH_4^+ results from less direct input of fertilizer to the streams, and the reduction in NO_3 probably results from the reduced effects on soil chemistry near the stream. A multi-year study in Florida evaluated the effectiveness of forestry BMPs for protecting aquatic ecosystems during intensive forestry operations, including fertilization. A bioassessment approach showed no significant differences in the aquatic ecosystem between the reference and the treated stream sections following fertilization.

Most of the detrimental effects of forest fertilization on water quality occur when fertilizer is applied directly to the streams. Precision silviculture is now being implemented throughout the U.S. Fertilizer prescriptions are made on a site-specific basis and are customized based on species, stand age, and soil conditions using sophisticated geographic information systems (GIS). The geographic coordinates of stands selected for fertilization are uploaded to satellite Global Positioning System (GPS) navigation equipment located in tractors and aircraft used to apply fertilizer. The GPS technology allows precise application of the fertilizer to the designated stand and enables the applicator to avoid fertilizer application to streams and the adjacent buffer strips (see **illustration above**). In this manner, the appropriate rate of fertilizer is applied only to the designated area which increases the efficiency of the fertilizer treatment and decreases the potential for adverse impact to aquatic systems.

Summary

Several dozen studies from around the world provide insights on the effects of forest fertilization on water quality. Forest fertilization can lead to modest increases in streamwater nutrient concentrations. The greatest increases come from 1) direct application of fertilizer to streams, 2) use of NO_3 forms of fertilizer, and 3) the application of high rates or repeated doses. Even in these situations, water quality impacts are generally small and transient. No evidence of changes in aquatic ecosystems has been reported from forest fertilization operations. Best management practices that include streamside management zones effectively protect water quality following forest fertilization. Modern precision silvicultural practices help ensure that the fertilizer is applied only to the desired portions of the forest, reducing the impacts on water quality. Because of the inherently higher native productivity and fertility of many agricultural soils, streams draining agricultural lands may have higher native nutrient concentrations compared to streams draining forested lands, whether or not the forests are fertilized. BC

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